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Abstract

This paper presents a fast estimation method for feedback level factor C of a self-mixing interferometry (SMI) system. The reconstruction of a displacement waveform using a SMI signal needs to know a C value. However, it is difficult to maintain a constant C value during the reconstruction process. We study the features of the reconstructed displacement waveforms incorporating different pre-set C values and classify waveforms into two types. Bisection method is introduced in our method for fast estimating C value. The effectiveness of our proposed method has been verified by both simulation and experimental data.

Keywords

estimation, method, for, feedback, level, factor, self, mixing, interferometry, system

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An estimation method for feedback level factor C of a self-mixing interferometry system

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ABSTRACT

This paper presents a fast estimation method for feedback level factor C of a self-mixing interferometry (SMI) system. The reconstruction of a displacement waveform using a SMI signal needs to know a C value. However, it is difficult to maintain a constant C value during the reconstruction process. We study the features of the reconstructed displacement waveforms incorporating different pre-set C values and classify waveforms into two types. Bisection method is introduced in our method for fast estimating C value. The effectiveness of our proposed method has been verified by both simulation and experimental data.

Keywords: semiconductor laser, feedback level factor, optical feedback, bisection searching algorithm, self-mixing interferometry

1. INTRODUCTION

Using a Self-Mixing Interferometry (SMI) system to measure metrological quantities such as velocity, vibration, displacement and absolute distance, is a new emerging sensing technique[1-3]. Comparing to commercial sensors with similar functions, SMI based sensing system is low-cost, self-aligned and simple to implement. Due to these merits, it has been drawing many researchers' attention[4-6]. The principle of SMI is based on self-mixing (SM) effect. It occurs when a small portion of laser beam is back-scattered or reflected by an external target and re-enters into the laser active cavity. The SM effect results in modulation on both amplitude and frequency of the emitted laser power. The modulated laser power, we call it as a Self-Mixing Signal (SMS).

Feedback level factor (FLF) (C) is an important parameter in a SMI system. The measurement method for C has been reported in many literatures[7-11]. In 1997, Merlo presented a calibration method to pre-calculate C value[7]. In 2004, Yu[8] proposed a simple and practical method for measuring Line-width Enhancement Factor (LEF) α , meanwhile, C value can also be estimated. In 2005, Xi and Yu[9] proposed a gradient-based optimization algorithm to estimate both C and α . However, these methods are all restricted to a certain feedback regime, such as weak or moderate regime. And they consider C value as a constant during the measurements. In practical, it is difficult to keep a constant C value during the measurements. In order to obtain real-time C values, Bes[10] developed a signal processing method under moderate feedback regime to joint estimate C , α and displacement using instantaneous power of the reconstructed signal discontinuities. But, the algorithm requires large computation of SMS samples. In 2009, an improved method based on the work in[10] was proposed in[11].

In this paper, we propose a fast estimation method for C values based on the analysis of the shape of reconstructed waveforms incorporating different pre-set C values. Applying a derivative operation firstly and then following a high-pass filtering, a pulse train is obtained from the waveforms. The magnitude and direction of an impulse can be used to indicate the deviation between the incorporating and the true C . Finally, a bisection searching algorithm is employed for fast determination of the true C values. The rest of paper is organized as follows: The theoretical model and basic theory of SMI are described in section 2. Our estimation method is proposed in section 3. Then, simulation and experiment results are presented in section 4 and section 5 respectively. Section 6 concludes the paper.

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2. BASIC THEORY

The SMI technology has been extensively studied by various scholars and a widely accepted mathematical model based on the Lang and Kobayashi equation[12] has been developed. For the use of this paper, the model is rewritten as below:

$$P(n) = P_0\left[1 + mI(n)\right] \tag{1}$$

$$I(n) = \cos\left(\phi_F(n)\right) \tag{2}$$

$$\phi_0(n) = \phi_F(n) + C\sin\left[\phi_F(n) + \arctan(\alpha)\right] \tag{3}$$

$$\phi_0(n) = 4\pi L(n)/\lambda_0 \tag{4}$$

The physical meanings of the parameters in the above model are described in Table 1.

In the above four equations, there are two important parameters : C and α . C is called feedback level factor (FLF) which indicates the influence of optical feedback on the behavior of a Laser Diode (LD)[13]. C is defined by[14, 15].

$$C = \eta \cdot \frac{\tau}{\tau_{SL}} \cdot (1 - R_1)\sqrt{\frac{R_2}{R_1}} \cdot \sqrt{1+\alpha^2} \tag{5}$$

Table 1. Meaning of parameters in Eq. (1)-(5)

n	Discrete time index.
$P(n)$	Power emitted by Laser Diode (LD) with feedback from external cavity.
P_0	Intensity emitted by the free running LD.
m	Modulation index for the laser intensity (typically $m \approx 10^{-3}$).
$I(n)$	Interference function which indicates the influence of the self-mixing effect on the emitted intensity.
C	Feedback Level Factor (FLF).
α	Line-width Enhancement Factor (LEF).
$\phi_F(n)$	Laser phase when the external target exists.
$\phi_0(n)$	Laser phase without feedback under free running conditions.
$L(n)$	Distance between the LD facet and the external target.
λ_0	Emitted laser wavelength without feedback.
τ	External round trip delay.
τ_{SL}	Round trip time in the LD.
η	The coupling coefficient of the feedback power.
R_1	Power reflectivity of the laser mirrors.
R_2	Power reflectivity of the external cavity surface.

FLF (C) determines the possible solution numbers of Eq. (3). For $0<C<1$, Eq. (3) gives a unique mapping between $\phi_F(n)$ and $\phi_0(n)$, that is, there is only a single solution in this situation. This range is also known as weak feedback regime. The waveform of a SMS is asymmetric sinusoidal like with slight abruptions. For $C>1$, there are more than two possible solutions in Eq. (3). This situation is referred to moderate regime or high regime in which the waveform reveals abrupt transitions with hysteresis. Meaning of parameters appeared in Eq. (5) is listed in Table 1.

α is known as line-width enhancement factor (LEF) which is a parameter used for characterizing a LD, such as the line-width, the chirp, the injection lock range, and the dynamic range. Both theory and its measurement method have been studied extensively[8, 16].

3. ESTIMATION METHOD FOR FEEDBACK LEVEL FACTOR C

The estimation method for C and α has been extensively studied in our previous works[8, 9, 17, 18]. In these works, C is assumed as a constant value. However, C is time varying in practical application. It is important to develop a method for real-time estimation of C values. The displacement carried in a SMS can be reconstructed using phase unwrapping technology. The reconstruction needs C values. We set different pre-estimated C values (denoted as $\hat{C}$) for the reconstruction. By studying the features of the reconstructed displacement signals $\hat{L}(n)$, we can classify $\hat{L}(n)$ into two types (shown in Fig. 1-c and Fig. 1-d). Fig. 1-c contains saw-tooth like fluctuations with $\hat{C}$ is greater than true C, Fig. 1-d has step like fluctuations with $\hat{C}$ is less than true C.

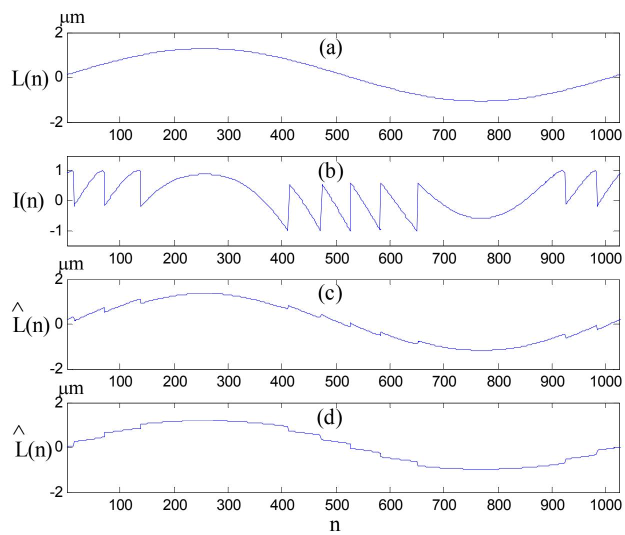

Figure 1. Reconstruction results with different pre-estimated $\hat{C}$ values. (a) original displacement $L(n)$, (b) SMS with $C=3,\alpha=4$, (c) reconstructed displacement $\hat{L}(n)$ using a over-estimated $\hat{C}$ $(\hat{C}>3)$, (d) reconstruction result $\hat{L}(n)$ using a low-estimated $\hat{C}$ $(\hat{C}<3)$.

We can see that the difference between $\hat{C}$ and true C results in fluctuations on the reconstructed result. In order to minimize fluctuations, we process the reconstructed signal by the following steps: 1. Differentiate it to obtain a signal $D(n)$, 2. Let $D(n)$ pass a high-pass filter to obtain fluctuations $D_F(n)$. Figure 2 shows the reconstruction result and the filtered fluctuations $D_F(n)$ with different pre-set $\hat{C}$ values. From Fig. 2 it can be seen that when $\hat{C}$ is getting closer to the true value of C, the magnitude of $D_F(n)$ becomes less and less. Also, we can see that the direction of $D_F(n)$ for $\hat{C}$ less than true C is always opposite to the case for $\hat{C}$ greater than true C.

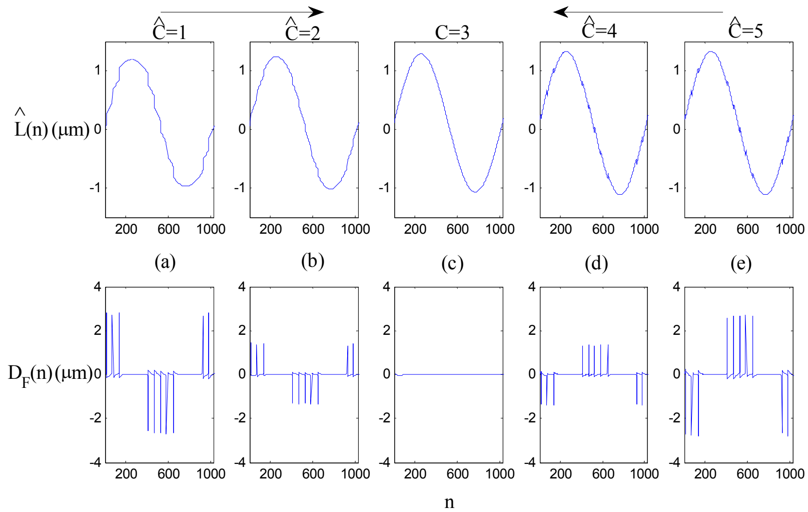

Figure 2. Displacement reconstruction results and the filtered fluctuations $D_F(n)$. (a) reconstruction result and $D_F(n)$ when $\hat{C}=1$, (b) reconstruction result and $D_F(n)$ when $\hat{C}=2$, (c) reconstruction result and $D_F(n)$ when $C=3$ which is the true value, (d) reconstruction result and $D_F(n)$ when $\hat{C}=4$, (e) reconstruction result and $D_F(n)$ when $\hat{C}=5$.

According to the above analysis, a fast C searching algorithm can be implemented based on a bisection method. Figure 3 shows the block diagram of our method. We usually set the searching range $[a,b]$ as $[1,30]$ which can cover moderate and strong feedback regimes. For weak feedback regime, C can be estimated by our previous proposed method[19].

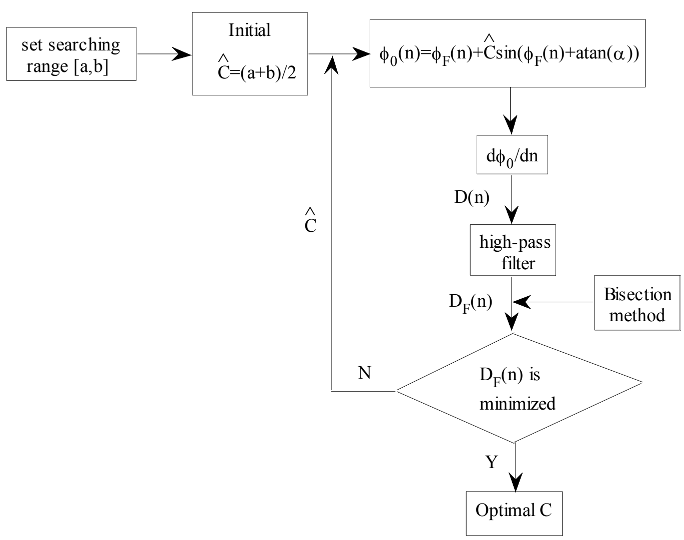

Figure 3. Block diagram for C estimation method.

4. SIMULATION

The proposed method has been firstly tested on simulation SMSs when C is a constant. Table 2 shows the simulation results when considering C is a constant. For each C, we simulated SMS 10 times with independent additive noise and use the average of the estimated $\hat{C}$ values as the estimation result.

We also test our method on a SMS which is generated by using a time-varying C. Fig. 4-c shows the estimation result $\hat{C}$ by using our method.

Table 2. Simulation results when C is a constant.

Moderate Feedback Regime					
True value of C	1.4	2.2	2.6	3.4	4.3
Estimated $\hat{C}$	1.4014	2.2018	2.5974	3.4008	4.2882
Std Dev.%	0.52	0.75	0.81	1.49	1.48
Strong Feedback Regime					
True value of C	4.8	5.3	5.8	6.2	6.9
Estimated $\hat{C}$	4.7968	5.3048	5.8296	6.2110	6.8954
Std Dev.%	2.53	2.82	2.3	3.16	4

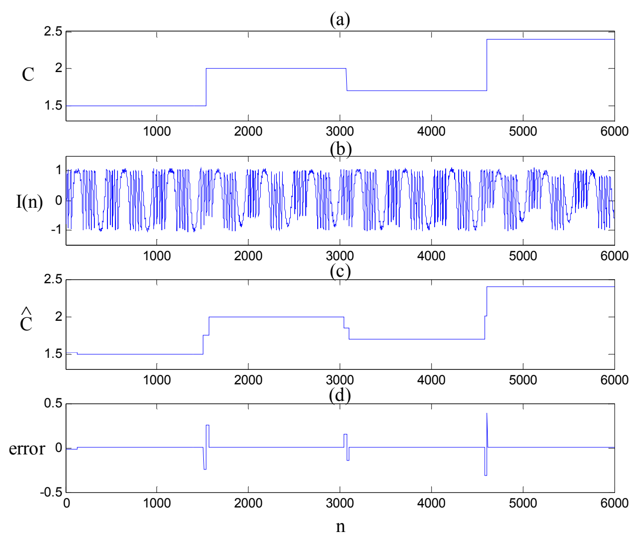

Figure 4. Estimation result when C is a variable. (a) actual time-varying C value, (b) a self-mixing signal with the time-varying C, (c) estimated $\hat{C}$ value, (d) residual error between actual C and estimated $\hat{C}$ value.

5. EXPERIMENT

Figure 5 shows the experimental set-up of our SMI system. The core part of the system consists of a Laser Diode (LD), a lens and an external vibrating target. The LD is biased with dc current and the external target vibrates harmonically by placing a loud speaker near it. The SMS is acquired by the Photo Diode (PD) connected to an amplifier and then obtained by computer via A/D converter with sampling frequency of 200KHz.

An experimental SMS and the estimation result of C are shown in Fig. 6. The reconstructed displacement of target is also shown in Fig. 6. We can see that the fluctuations have been greatly reduced by using the estimated $\hat{C}$ values.

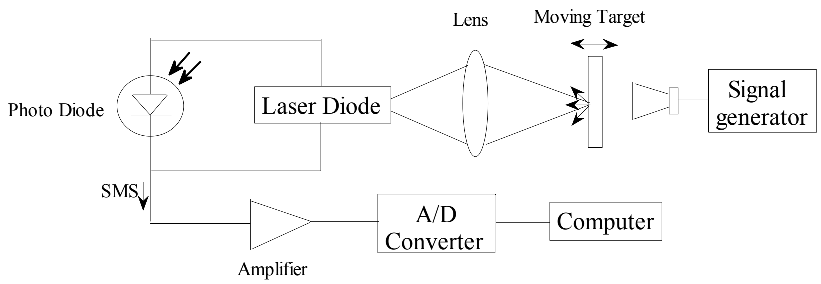

Figure 5. A SMI experimental set-up.

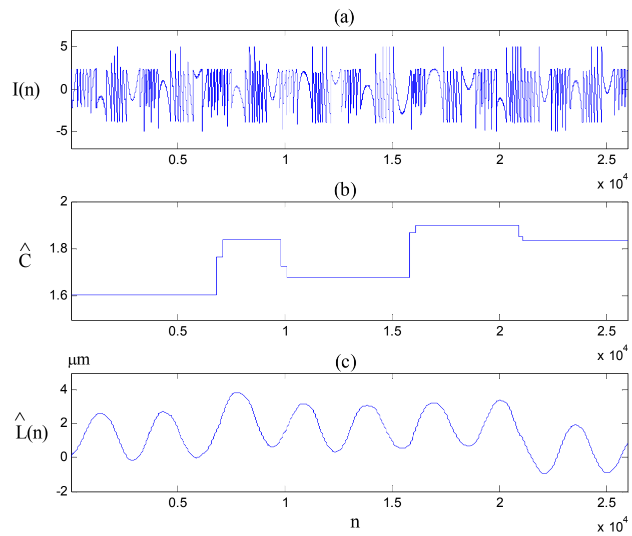

Figure 6. Experimental estimation result. (a) a SMS acquired from experimental set-up, (b) estimation result $\hat{C}$, (c) reconstructed displacement by using the estimated $\hat{C}$ values.

6. CONCLUSION

This paper presents a fast estimation method for the feedback level factor (C). By using advance signal processing method and bisection method, we can estimate time-varying C values rapidly based on the analysis of the features of reconstructed waveform incorporating different pre-set $\hat{C}$ values. The effectiveness of our proposed method has been tested by both simulations and experiments.

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